

## THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

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### ABSTRACT

The ASCE-Environmental and Water Resources Institute Technical Committee: Evapotranspiration in Irrigation and Hydrology, in cooperation with the Water Management Committee of the Irrigation Association, has defined and established a standardized reference evapotranspiration (ET) equation. The purpose of the equation and standardized calculation is to bring commonality to the methodology for reference ET calculation and to provide a standardized basis for determining or transferring crop coefficients for agricultural and landscape use.

The basis of the standardized reference ET equation is the ASCE Penman-Monteith (ASCE-PM) method of ASCE Manual 70 (Jensen et al., 1990). For the standardization, the ASCE-PM method is applied to two types of reference surfaces (short and tall) representing clipped grass (a short, smooth crop) and alfalfa (a taller, rougher agricultural crop) and the equation is simplified in a reduced form of the ASCE-PM. Provisions and recommendations are made for application of the method to hourly and daily calculation time steps. Standardized calculations for all intermediate parameters are provided as well as guidelines on assessing weather data integrity and estimating values for missing data.

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## INTRODUCTION

Reference evapotranspiration ( $ET_{ref}$ ) is the rate at which readily available soil water is vaporized from specified vegetated surfaces (Jensen et al., 1990). During the last quarter of the 20<sup>th</sup> century,  $ET_{ref}$  was represented by ET measured from or predicted for full-cover alfalfa or clipped cool-season grass (Jensen, 1974, Doorenbos and Pruitt, 1977, Wright, 1982) and depicted as  $ET_r$  and  $ET_o$ , respectively. There have been traditionally two types of reference crops (grass and alfalfa) and nine major reference methodologies (1963 Penman, FAO-24 Penman, 1982 Kimberly Penman, CIMIS Penman, ASCE Penman-Monteith, FAO-56 Penman-Monteith, Jensen-Haise, 1985 Hargreaves and evaporation pan) that have evolved over the past fifty years (Jensen et al., 1990), each having large groups of followers and related crop coefficients. In addition to a range of growing conditions and basic  $ET_{ref}$  equations, there have been a myriad of procedures used to predict net radiation, vapor pressure deficit and other equation parameters in the various methods. The precise ET rate measured from or predicted for reference surfaces has varied because the grass and alfalfa references have been living crops that exhibit changes in height, leaf area, stage of growth, age, variety, and stomatal behavior and are affected by soil wetness.

Hourly and daily computation time-steps are in common usage and it is important that hourly calculations, when summed for a day, agree closely with calculations made with daily time-step calculations.

In May 1999, The Irrigation Association (IA) requested the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) Technical Committee on Evapotranspiration in Irrigation and Hydrology Committee to establish and define a benchmark reference evapotranspiration equation to improve transferability and application of crop coefficients. IA envisioned an equation that would be accepted by the U.S. scientific community, engineers, legal community, policy makers, and other end users. The equation would be applicable to agricultural and landscape irrigation and would facilitate the use and transfer of crop and landscape coefficients. IA requested recommendations for incorporating existing crop and landscape coefficients and reference ET calculations and guidelines for where climatic data are limited.

In response to the request by IA, an ASCE-EWRI Task Committee (ASCE-ET) comprised of the authors of this paper prepared the EWRI (2001) standardization report. The report provides detail on development of the ASCE Standardized equation, recommendations on use of the equation, and example calculations. In addition, the report provides guidelines for assessing integrity of weather data used for estimating ET and methodologies that can be used where data are limited or missing. Previous papers describing the standardization effort have been jointly authored by several members of ASCE-ET (Allen, et al., 2000; Walter, et al., 2000; Itenfisu, et al., 2000; 2003).

## REFERENCE ET STANDARDIZATION

During the past decade, for convenience and reproducibility, the reference surface has been expressed as a hypothetical crop having specific characteristics (Smith et al., 1991, Allen et al., 1994, Allen et al., 1998). In the context of the standardization, reference evapotranspiration has been defined by EWRI (2001) as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation.

Issues and requirements in the selection of an equation to represent a standardized definition of  $ET_{ref}$  and standardized procedures for supporting calculations were discussed in depth by ASCE-ET (Allen et al., 2000, EWRI, 2001). Requirements for the standardization were that the adopted procedure be understandable, defensible, accepted by science/engineering communities, relatively simple and easy to use, and based on existing and historical data and technology. The challenge was to select one or more equations that satisfy the selection criteria.

ASCE-ET recommended that the equation be referred to as the "Standardized Reference Evapotranspiration Equation" ( $ET_{sz}$ ). ASCE-ET is of the opinion that use of the terms *standard* or *benchmark* may lead users to assume that the equation is intended for comparative purposes (i.e., a level to be measured against). Rather, the use of the term "standardized" infers that the computation procedures have been fixed, and not that the equation is a standard or a benchmark or that the equation has undergone the degree of review in the approval process necessary for standards adopted by ASCE, ASAE, American National Standards Institute, or the International Organization for Standardization.

ASCE-ET concluded that two standardized  $ET_{ref}$  surfaces were needed to serve the needs of the agricultural and landscape communities and to provide for continuity with past  $ET_{ref}$  usage. The two adopted  $ET_{ref}$  surfaces are (1) a short crop (similar to full-cover clipped grass) and (2) a tall crop (similar to full-cover alfalfa). Additionally, ASCE-ET recognized that an equation capable of calculating both hourly and daily  $ET_{ref}$  was needed. The ASCE Standardized Reference ET Equation models each of the two reference surfaces using a single equation with fixed constants and standardized computational procedures. Accordingly, the two surfaces are defined as:

Standardized Reference Evapotranspiration, Short ( $ET_{os}$ ): Reference ET for a *short* crop with a height of 0.12 m and fixed surface resistance (similar to full-cover clipped grass).

Standardized Reference Evapotranspiration, Tall ( $ET_{rs}$ ): Reference ET for a *tall* crop with a height of 0.50 m and fixed surface resistance (similar to full-cover alfalfa).

The two reference surfaces are similar to known full-cover crops of alfalfa and clipped grass that have received widespread use as  $ET_{ref}$  across the United States. Each reference has unique advantages for specific applications.

### DEFINITION OF THE EQUATION

Following various meetings, reviews of papers and analyses and deliberations, ASCE-ET selected the ASCE Penman-Monteith (ASCE-PM) equation (Jensen et al, 1990) as the basis for the standardization. Justification and considerations are summarized in EWRI (2001), Allen et al. (2000) and Walter et al. (2000). The Standardized Reference Evapotranspiration Equation is intended to simplify and clarify the presentation and application of the method and is a reduced form of the ASCE-PM equation, similar to the form used in FAO Irrigation and Drainage Paper No. 56. As a part of the standardization, the ASCE-PM equation and associated equations for calculating aerodynamic and bulk surface resistance were combined and condensed into a single equation that is applicable to both reference surfaces. As used in EWRI (2001), the term  $ET_{sz}$  refers to both  $ET_{os}$  and  $ET_{rs}$  and is presented as:

$$ET_{sz} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)} \quad (1)$$

where:

- $ET_{sz}$  = standardized reference crop evapotranspiration for short ( $ET_{os}$ ) or tall ( $ET_{rs}$ ) surfaces ( $\text{mm d}^{-1}$  for daily time steps or  $\text{mm h}^{-1}$  for hourly time steps),
- $R_n$  = calculated net radiation at the crop surface ( $\text{MJ m}^{-2} \text{d}^{-1}$  for daily time steps or  $\text{MJ m}^{-2} \text{h}^{-1}$  for hourly time steps),
- $G$  = soil heat flux density at the soil surface ( $\text{MJ m}^{-2} \text{d}^{-1}$  for daily time steps or  $\text{MJ m}^{-2} \text{h}^{-1}$  for hourly time steps),
- $T$  = mean daily or hourly air temperature at 1.5 to 2.5-m height ( $^{\circ}\text{C}$ ),
- $u_2$  = mean daily or hourly wind speed at 2-m height ( $\text{m s}^{-1}$ ),
- $e_s$  = saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature,
- $e_a$  = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),
- $\Delta$  = slope of the saturation vapor pressure-temperature curve ( $\text{kPa } ^{\circ}\text{C}^{-1}$ ),
- $\gamma$  = psychrometric constant ( $\text{kPa } ^{\circ}\text{C}^{-1}$ ),
- $C_n$  = numerator constant that changes with reference type and calculation time step, and

$C_d$  = denominator constant that changes with reference type and calculation time step.

Table 1 provides values for  $C_n$  and  $C_d$ . The values for  $C_n$  consider the time step and aerodynamic roughness of the surface (i.e., reference type). The constant in the denominator,  $C_d$ , considers the time step, bulk surface resistance, and aerodynamic roughness of the surface (the latter two terms vary with reference type, time step and daytime/nighttime).  $C_n$  and  $C_d$  were derived by simplifying several terms within the ASCE-PM equation and rounding the result. Daytime is defined as occurring when the average net radiation,  $R_n$ , during an hourly period is positive. Equations associated with calculation of required parameters in Eq. 1, the detailed derivation of the parameters in Table 1 and simplification of the terms listed in Table 2 are explained in detail in EWRI (2001). In most cases, equations for parameters are consistent with those used by FAO-56 (Allen et al., 1998).

### USE OF THE STANDARDIZED EQUATION

Based on an intensive review of reference evapotranspiration calculated at 49 sites throughout the United States (described in the following section), ASCE-ET found the standardized equation to be reliable and recommended its use for:

- Calculating reference evapotranspiration and, in turn, crop evapotranspiration ( $ET_c$ )
- Developing new crop coefficients
- Facilitating transfer of existing crop coefficients

### CALCULATING STANDARDIZED REFERENCE CROP EVAPOTRANSPIRATION

EWRI (2001) describes data requirements, equations, and procedures necessary for calculating  $ET_{sz}$  on a daily and hourly time step. Selection of the appropriate time step is a function of data availability, climate, the intended application, and user preference.

Table 1. Values for  $C_n$  and  $C_d$  in Eq. 1

Calculation Time Step	Short Reference, $ET_{os}$		Tall Reference, $ET_{rs}$		Units for $ET_{os}$ , $ET_{rs}$	Units for $R_n$ , G
	$C_n$	$C_d$	$C_n$	$C_d$		
Daily	900	0.34	1600	0.38	mm d <sup>-1</sup>	MJ m <sup>-2</sup> d <sup>-1</sup>
Hourly during daytime	37	0.24	66	0.25	mm h <sup>-1</sup>	MJ m <sup>-2</sup> h <sup>-1</sup>
Hourly during nighttime	37	0.96	66	1.7	mm h <sup>-1</sup>	MJ m <sup>-2</sup> h <sup>-1</sup>

Table 2. ASCE Penman-Monteith Terms Standardized for Application of the Standardized Reference Evapotranspiration Equation

Term	$ET_{os}$	$ET_{rs}$
Reference vegetation height, h	0.12 m	0.50 m
Height of air temperature and humidity measurements, $z_h$	1.5 – 2.5 m	1.5 – 2.5 m
Height corresponding to wind speed, $z_w$	2.0 m	2.0 m
Zero plane displacement height	0.08 m	0.08 m <sup>a</sup>
Latent heat of vaporization	2.45 MJ kg <sup>-1</sup>	2.45 MJ kg <sup>-1</sup>
Surface resistance, $r_s$ , daily (24-hour)	70 s m <sup>-1</sup>	45 s m <sup>-1</sup>
Surface resistance, $r_s$ , daytime (hourly or shorter)	50 s m <sup>-1</sup>	30 s m <sup>-1</sup>
Surface resistance, $r_s$ , nighttime (hourly or shorter)	200 s m <sup>-1</sup>	200 s m <sup>-1</sup>
Value of $R_n$ for predicting daytime	> 0	> 0
Value of $R_n$ for predicting nighttime	≤ 0	≤ 0

<sup>a</sup> The zero plane displacement height for  $ET_{rs}$  assumes that the wind speed measurement is over clipped grass, even though the reference type is tall. When wind speed is measured over a surface having vegetation taller than 0.3 m, the “full” ASCE-PM method [Eq. B.1 of EWRI (2001)] be employed for  $ET_{rs}$ .

Appendix B of EWRI (2001) provides background on the development of the standardized form of the PM equation. The full form of the ASCE-PM equation, which includes explicit terms for aerodynamic and surface resistance, is not required, nor is it recommended, for calculation of  $ET_{sz}$ . The full form of the ASCE-PM equation is recommended when ET is measured over grass or alfalfa vegetation having substantially different height than the 0.12 m height defined for the short reference (grass) or 0.50 m height defined for the tall reference (alfalfa). Values for vegetation height are fixed in the standardized equation.

The calculation of  $ET_{sz}$  requires measurements or estimates for air temperature, humidity, solar radiation, and wind speed. These parameters are considered to be the minimum requirements to estimate  $ET_{os}$  and  $ET_{rs}$ . EWRI (2001) provides recommendations on preferred types of humidity data and guidelines for calculation of the vapor pressure deficit given various types of humidity data. The report also provides an update on recommended calculation of potential solar radiation under clear sky conditions. ASCE-ET investigated in detail procedures and coefficients for calculation of net radiation and soil heat flux as it impacts hourly calculations. Recommendations were based on committee consensus.

The accuracy of any ET calculation depends on the quality of weather data. EWRI (2001) recommends, when possible, that weather data be measured at stations located in open, well-watered settings and with good quality control and quality assurance procedures in place. Suggestions for assessing and improving integrity of collected data are described in Appendices D and E of EWRI (2001). Appendix D provides guidelines for evaluating the weather station site and the possible impact upon measured meteorological parameters. Appendix E provides guidelines for replacing missing data and data judged to be of poor quality.

### EVALUATION OF THE STANDARDIZED EQUATION

As part of the ASCE-ET standardization effort, the  $ET_{sz}$  definition was compared against other widely-used equations over a wide range of climatic conditions across the United States. Equations compared were the 1982 Kimberly Penman (Wright, 1982), the 1963 Penman (Penman, 1963), the 1985 Hargreaves equation (Hargreaves et al., 1985), the CIMIS hourly Penman (Snyder and Pruitt, 1985), and the FAO-56 Penman-Monteith (Allen et al., 1998). The analysis utilized 82 site-years of data from 49 sites in the states of Arizona, California, Colorado, Idaho, Montana, Nebraska, Oklahoma, Oregon, South Carolina, Texas, Utah, Washington, Florida, Georgia, Illinois, and New York. The data were collected by ASCE-ET members and other cooperators and represent agricultural weather stations. The data span a wide range of elevation (2 to 2,895 m), mean annual precipitation (152 to 2,032 mm) and peak monthly ET (2.78 to 9.68 mm d<sup>-1</sup>).

Daily and hourly ET amounts from all sites were compared against  $ET_{sz}$  as computed by the ASCE-PM equation to assess comparative behavior across the various climates. Evaluations were compiled by Itenfisu and Elliott (Itenfisu et al., 2000, 2003) of the Biosystems and Agricultural Engineering Department at Oklahoma State University. Several equation-to-equation comparisons were conducted. The key comparisons were daily ET versus daily  $ET_{sz}$ , summed hourly ET versus daily  $ET_{sz}$  and summed hourly ET versus daily ET (for the same method). The comparisons were made for both  $ET_o$  and  $ET_r$ . Statistics evaluated included the ratio of each equation's ET estimate to that of the full-form ASCE-PM equation, the Root Mean Square Difference (RMSD) and the RMSD

as a percentage of ASCE-PM. For each of the site years, the statistics were summarized over the growing season and if available, for the full year.

The results showed that the ratio of the summed hourly  $ET_{os}$  to the daily  $ET_{os}$  ranged from 0.94 to 1.05 and averaged 1.00 annually over all sites and time periods. For the growing season, the range was from 0.87 to 1.08 and averaged 1.00. The  $ET_{os}$  was as defined in Equation (1) and Table 1. For  $ET_{rs}$ , the ratio of summed hourly computed  $ET_{rs}$  to the daily  $ET_{rs}$  ranged from 0.90 to 1.07 and averaged 0.99 for growing seasons. The "full-form" ASCE-PM equation, applied with the same values for surface resistance for both hourly and 24-hour time periods, had ratios of summed hourly  $ET_o$  to daily  $ET_o$  that ranged from 0.86 to 1.01 over all locations and averaged 0.95 annually. For the growing season, the range was from 0.76 to 1.05 and averaged 0.95. The ASCE-ET committee concluded that hourly surface resistance values of 50 and 200  $s\ m^{-1}$  (day and nighttime) for  $ET_{os}$  and hourly surface resistance values of 30 and 200  $s\ m^{-1}$  (day and nighttime) for  $ET_{rs}$  provided hourly computed  $ET_{sz}$  that, when summed, best matched daily computations (Tables 1 and 2). Surface resistances for daily computations were fixed at 70  $s\ m^{-1}$  for  $ET_{os}$  and 45  $s\ m^{-1}$  for  $ET_{rs}$ . Additional comparisons and summaries are in Itenfisu et al. (2000, 2003).

### APPLICATION OF CROP COEFFICIENTS

Crop coefficients ( $K_c$ ) and landscape coefficients available in the literature are referenced to either clipped grass or full-cover alfalfa. Crop coefficients for the two reference types are not interchangeable without appropriate adjustment. Grass-based crop coefficients should be used with  $ET_{os}$ , and alfalfa-based coefficients should be used with  $ET_{rs}$ . If a calculated or measured reference other than  $ET_{os}$  or  $ET_{rs}$  was used to develop the crop coefficients, it must be established that the equation or measurements provide values that are equivalent to  $ET_{os}$  or  $ET_{rs}$ . It is important to establish the differences between ET equations since some equations developed to predict grass or alfalfa reference ET may not agree exactly with  $ET_{os}$  or  $ET_{rs}$  during all time periods or under all climatic conditions.

$K_c$  values that can be used with  $ET_{os}$  without adjustment are those reported in FAO-56 (Allen et al., 1998) and ASCE Manual 70 (Jensen et al., 1990, Table 6.8). Coefficients that can be used as is with  $ET_{os}$  for most practical applications are those reported by FAO-24 (Doorenbos and Pruitt, 1977) and SCS NEH Part 623 Chapter 2 (Martin and Gilley, 1993). Coefficients based on the CIMIS Penman equation (Snyder and Pruitt, 1992) for agricultural crops (Snyder et al., 1989a,b) should not require adjustment for use with  $ET_{os}$ , since they compare closely with those of FAO-56. Landscape  $K_c$ 's based on the CIMIS Penman equation should be verified before use with  $ET_{os}$ .  $K_c$  values that can be used as is with  $ET_{rs}$  for most practical applications are those reported by Wright (1982) and ASCE Manual 70 (Jensen et al., 1990, Tables 6.6 and 6.9). However, questions remain to be answered regarding direct transferability of crop coefficients,

including those for  $ET_{rs}$ . The transferability of crop coefficients between regions and between reference definitions is a complex issue that needs additional study. ASCE-ET has formed a Task Committee whose task will be in part to address that issue.

### SUMMARY AND CONCLUSIONS

The ASCE Penman-Monteith equation of Jensen et al. (1990) has been used to define standardized calculations for reference evapotranspiration. The equation is physically based and provides consistent and standardized definition of reference ET for short and tall reference surfaces. The intent of the standardization is to facilitate transfer of crop and landscape coefficients within and between regions of the United States and to provide an agreed upon and stated methodology for common calculation of reference ET.

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